Invited Paper

A Decade of Interdisciplinary Process Studies

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ABSTRACT

During the past decade, interdisciplinary process studies have been conducted in many regions of the world oceans. The focus of this review is on studies which have utilized new and emerging optical sensors and systems which have been deployed from multiple sampling platforms. These studies have led to increased understanding of ocean processes which are of interest for problems concerning 1) fundamental ocean optics, 2) remote sensing of the ocean, 3) the ocean's ecology and renewable resources, 4) the ocean's role in global climate change, and 5) pollution and its effects. Here we describe some of the methodologies which have enabled advances and provide brief summaries of a few studies in diverse geographical regions.

KEYWORDS: oceanography, interdisciplinary, regional, processes, technologies, optics, acoustics

1. INTRODUCTION

Interdisciplinary process studies have been conducted in several regions of the world oceans during the past decade. Regional studies allow oceanographers to focus on processes which are either unique to or more dominant in a given oceanic domain (e.g., equatorial waves, monsoons, coastally trapped waves, etc.). These studies have been motivated by interest in a host of ocean problems which can only be studied by combining the collective expertise of oceanographers from subdisciplines including physics, chemistry, and biology. The problems of interest involve a multiplicity of variables and span ten orders of magnitude in temporal and spatial scale.[1-3] Progress in understanding how the ocean functions as a dynamic system has been limited to a large degree by sampling capabilities. While many of the basic and larger scale physical and chemical processes are reasonably well understood, the physics and chemistry relevant to the smaller scales and individual organisms remain a challenge. It has become a well accepted notion that advancement of understanding of biological and optical processes requires concurrent, interdisciplinary sampling from a suite of platforms.[3-5] Fortunately, major technological advances have been made in the areas of applied optics and acoustics along with data acquisition, storage, and telemetry.[4,6] The various studies described herein have all benefited from emerging technologies. Problems of interest concern 1) fundamental ocean optics, 2) remote sensing of the ocean, 3) the ocean's ecology and renewable resources, 4) the ocean's role in global climate change, and 5) pollution and its effects. Some of the methodologies which have enabled advances are described herein and are illustrated through examples of a few studies in different geographical regions. Because of limited space, our review is by no means comprehensive; thus several important studies could not be treated. The reader is directed to other review papers and reports for further information.[1-12]

2. METHODOLOGIES

Optical and acoustical sensors and systems have been developed for a variety of oceanographic applications over more than a decade. One of the more important motivations has been to develop *in situ* optical sensors which can be used to relate in situ water properties such as chlorophyll pigment concentration to upwelled water-leaving radiance measured by satellite- or airplane-based ocean color sensors.[8,13,14] Another need is to determine light available for photosynthesis by phytoplankton, which is important for the ecology of and the carbon uptake by the ocean as well as heating effects.[8] There is also increasing use of optical and acoustical measurements for pollution studies and monitoring.[6,15,16] Presently available optical and acoustical instruments can be used to sample organisms ranging in size from a few microns to meters virtually continuously.[1-3] Many of these are small enough to be deployed from shipboard profiling and towed packages, moorings, drifters, remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs). The beam transmissometer (beam c at 660nm) and stimulated fluorometer have been used on CTD profilers, drifters, and moorings. Within the past few years, a new generation of spectral optical sensors and systems have been developed to measure both inherent and apparent optical properties spectrally.[5,8] Several of these are designed to measure the same wavelengths as those of satellite color imagers (e.g., SeaWiFS). In addition, it may be possible to differentiate major taxa of phytoplankton using spectral signatures. One of the exciting aspects of these measurements is the potential for attaining optical closure.[17] Spectral fluorometers with multiple excitation and emission wavelengths are now being used to attempt to characterize water constituents such as colored dissolved organic material.[18,19] Other optical devices are designed to measure distributions of zooplankton. These include optical plankton counters which pass a sheet of light through a test volume to a detector and video plankton recorders which utilize video cameras.[11] Multi-frequency acoustical devices are being used to measure zooplankton and fish in size classes from about 100µm to a meter.[21,22] Acoustic Doppler current profilers (ADCPs) can provide backscatter data relevant to limited size classes of zooplankton.[20,22,23]

3. REGIONAL STUDIES

The study of Gulf Stream warm core rings was significant not only because of the importance of mesoscale dynamics, but also because some of the first profile measurements of apparent spectral radiation were made.[24,25] Satellite measurements of sea surface temperature and color (Coastal Zone Color Scanner, CZCS) were obtained as well and thus enabled synoptic observations relevant to phytoplankton and optical properties of the upper ocean. The Biowatt program was conducted in the Sargasso Sea (34°N, 70°W) in 1985 and 1987 and dealt with variability of phytoplankton and optical properties including bioluminescence on time scales ranging from minutes to the seasonal cycle.[13,25-28] Mooring time series measurements included several optical variables (e.g., chlorophyll fluorescence, beam attenuation, PAR, spectral radiation, etc.). Episodic phytoplankton blooms and busts were observed. The downward propagation of an inertial wave along a front resulted in an apparent increase in productivity as nutrients were entrained into the euphotic layer.[29] Smith et al.[13] demonstrated the utility of moored measurements for developing color satellite algorithms. Using mooring data, Marra et al.[27] and Waters et al.[28] estimated virtually continuous primary productivity and Wiggert et al.[30] quantified the effect of temporal undersampling on primary productivity determinations. Although no color satellite imager was in orbit, Geosat altimetry data were valuable for interpretation of mooring data at the site which was subject to warm outbreaks and mesoscale features associated with the Gulf Stream.[26] The British have conducted several studies devoted to open ocean mesoscale features and associated local upwelling on the eastern side of the North Atlantic using towed systems (Sea Rover and SeaSoar) simultaneously with ADCP measurements.[22,31] These studies have allowed quantification of scales of patchiness (primary at 100-300km and secondary between 10-20km) and associations between eddies and fronts with high concentrations of chlorophyll fluorescence. Other similar studies, but with even more optical sensors, have been conducted in this region with the Undulating Oceanographic Recorder.[32] The U.S. JGOFS Bermuda Atlantic Time-series Study (BATS) was not specifically planned as a process studies program.[33] However, it has been effectively used to study a variety of phenomena including the seasonal evolution of the diffuse attenuation coefficient spectrum and colored dissolved material[34,35] and the effects of the passage of Hurricane Felix.[36] The Marine Light in the Mixed Layer (MLML) program had many of the same objectives as the Biowatt program[37]; however the setting was at a high latitude (south of Iceland: 59°N 21°W) in 1989 and 1991. The JGOFS North Atlantic Bloom Experiment (NABE) was conducted in 1989 with its most northern stations near the MLML site. This high latitude, dynamic location presented a major challenge for moored observations, but excellent bio-optical and physical time series were obtained along with shipboard profile and tow-yo data and P-3 aircraft overflight observations. The spring shoaling of the mixed layer was dramatic[38] (from ~550m to ~50m within 5 days). One of the interesting processes revealed from the mooring observations was the onset of a phytoplankton bloom (apparently associated with modest near surface stratification) prior to the major springtime shoaling of the mixed layer and the seasonal spring bloom. Furthermore, an increase of near surface temperature of 0.2°C was associated with the phytoplankton increase.[39] Spatial maps of physical and bio-optical variables were obtained using SeaSoar, tow-yo, and Paravane systems. The SeaSoar and Paravane were able to map over hundreds of kilometers and demonstrated the importance of water mass variability and mesoscale eddies on bio-optical characteristics[40] (e.g., Washburn et al., in prep.). In addition, the Paravane obtained bioluminescence data throughout the upper 150m and showed that bioluminescence was quite patchy. The tow-yo results show much smaller scale features. During these observations, bio-optical characteristics were uniformly distributed within the mixed layer, but showed significant horizontal variability at scales less than 10km due to the interleaving of water masses within the region (Jones et al., in prep.). The Iceland-Faeroes front was studied in 1990 using simultaneous SeaSoar and ADCP observations by Roe and Griffiths[22] and Roe et al.[23] These observations provided quantitative evidence of enhanced biomass near the front and its associated eddies along with associated large vertical water velocities and vertical migration of organisms.

The equatorial Pacific has been the subject of several international studies (e.g., JGOFS) in recent years. The region is especially interesting because of the high degree of variability associated with equatorial waves (Kelvin waves, Tropical Instability Waves or TIWs, etc.) and the global impact of the El Nino-Southern Oscillation (ENSO) phenomenon. The establishment of the Tropical Ocean-Global Atmosphere (TOGA) array of moorings in the equatorial waveguide has lead to major advances in predicting El Ninos. One of the earliest mooring sites (0°, 140°W) was used for JGOFS and NOAA studies for an 18-month period (1992-1993) during which both El Nino and non-El Nino conditions prevailed.[41,42] Moored optical measurements were used to produce high resolution (few minutes) time series of PAR, chlorophyll fluorescence, and primary productivity[30] (Foley et al., in prep.). These measurements revealed large variations in bio-optical properties and primary productivity which were likely associated with Kelvin waves and TIWs. In addition, drifters with radiometers were released at the mooring site and provided a Lagrangian view of increasing biomass with increasing distance from the equator as TIWs moved through the site. A dramatic "line in the sea" resulted in part from high concentrations of phytoplankton (*Rhizosolenia sp.*, a buoyant diatom) north of the equator.[43] The line traced the northern edge of a TIW and was evident in measurements made from ship, aircraft, satellite, and Space Shuttle Atlantis. The biologically rich front was located between the colder, upwelled waters to the south and warmer less productive waters to the north.

One of the most recent process studies was conducted in the Arabian Sea as part of an international program (i.e., U.S. JGOFS and ONR, several other nations). An array of five moorings (50km square) was used to collect data spanning a year-long period, thus sampling both the northeast and southwest monsoons. The central mooring (15° 30'N, 61° 30'E), which included bio-optical moored sensors, was located under the climatological axis of the atmospheric Findlater Jet. Bi-annual mixed layer shoaling and deepening of the mixed layer was observed with associated phytoplankton bloom cycles.[44] One of the interesting results of this study was the observance of mesoscale features (e.g., filaments, eddies) of apparent coastal origin which influenced the mooring site roughly 550km away.[45,46] SeaSoar surveys (Brink et al. and Jones et al., in prep.) were able to characterize these features with variability in physical and bio-optical properties on horizontal scales from 10km to a few hundred km. TOPEX Poseidon altimetry data and underway shipboard ADCP data also provided important information concerning mesoscale features for this energetic and biologically rich region. Finally, Roe et al.[23] have reported extreme biological layering (16 distinct layers in upper 350m) off of Oman based upon backscattering acoustic data, further illustrating the complexity of the Arabian Sea.

A comprehensive interdisciplinary ocean survey was conducted in the Bellingshausen Sea as part of the British Ocean Flux Study (BOFS) in the austral spring of 1992 by Weeks et al.[47] A SeaSoar equipped with bio-optical as well as physical sensors and a ship-mounted ADCP were used to quantify scales of variability and correlations among physical properties and currents and phytoplankton and zooplankton distributions. The study focused on a major frontal feature (67-68° 30'S and 84-88°W). Elevated phytoplankton and zooplankton concentrations were well correlated in the surface waters, a result which is not always found. The light field and chlorophyll distributions were important factors affecting zooplankton at greater depth. This study reinforced the need for concurrent sampling of physics and biology and the utility of ship-mounted ADCPs. Upcoming international studies in the Southern Ocean are to be conducted as contributions of JGOFS and GLOBEC.

The coastal ocean presents optical oceanographers with several interesting, though challenging, problems. For example, particulate and dissolved organic matter of terrestrial origin are important and biomass is typically more diverse and abundant. In addition, the physical scales of the coastal ocean are shorter, response to wind forcing is more rapid, and tides and surface waves are quite important. The west coast of the U.S. has been a region of many important interdisciplinary studies over the past decade. For example, the Coastal Transition Zone (CTZ) experiment examined the development of filaments and eddies off of central California using satellite sensing, shipboard profiling, and towed systems.[48] In addition a drifter, equipped with bio-optical sensors, was deployed and recorded the evolution of biomass and optical properties as it drifted seaward.[49] Bio-optical observations provided some of the first hints of subduction processes that are associated with upwelling filaments.[50] Beam attenuation coefficient and chlorophyll maxima appeared well below the euphotic zone indicating that upper layer water was being transported downward as well as horizontally.[51] Another major interdisciplinary sampling program, which employs new technologies, is underway in coastal waters off Monterey, California (Chavez et al). Optical methods have also been applied to pollution studies in the coastal zone. Off the coast of Los Angeles, one of the most severely impacted coastal regions in the U.S, optical sensors have been deployed from towed systems, moorings with telemetry, bottom tripods, airplane color scanners, and satellite imagers. These various platforms have been used to study how sewage outfall plumes disperse[15,16] and how sediments are resuspended.[52] The use of bio-optical data has allowed partitioning of water masses using beam attenuation and chlorophyll fluorescence as well as salinity and temperature relationships.[15,16] The discovery of sediment resuspension resulting from near bottom internal solitary waves was possible because of high frequency optical sampling.[52] An extension of the work off the Los Angeles coast has been conducted off Honolulu. In this study, a spectral absorption and attenuation meter, a stimulated spectral fluorometer (6 wavelengths of excitation and 16 wavelengths of emission), and a particle sizing instrument were used to study an outfall plume and to characterize the particle fields associated with both plume and ambient waters.[19] The fate of continental shelf particulate matter (e.g., carbon) has been the subject of two major interdisciplinary experiments in the Middle Atlantic Bight off the east coast of the U.S.[53] The second of these, Shelf Edge Exchange Processes-II, was conducted in 1988 and 1989 and utilized moored ADCP and bio-optical systems (e.g., transmissometers and fluorometers). The general finding was that the major portion of primary production landward of the 90-m isobath was not transported seaward, negating the experiment's working hypothesis (at least for this study area[54]). The time series data indicated that the phytoplankton and zooplankton concentrations were highly variable with a continuum of energy at all frequencies and generally low coherences between these variables and local physics.[55] The ONR Coastal Mixing and Optics (CMO) program is presently being conducted south of Martha's Vineyard, Massachusetts and should provide another important data set as a comprehensive suite of optical and physical measurements are being collected from several platforms. Interestingly, Hurricane Edouard passed over the site in September, 1996 and preliminary results show a major sediment resuspension event and large variations in optical properties. Other relevant east coast studies presently underway include the George's Bank GLOBEC experiment and the Ocean Margins Program off Cape Hatteras.

4. ACKNOWLEDGMENTS

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5. REFERENCES

1. T. Dickey, "Recent advances and future directions in multidisciplinary *in situ* oceanographic measurement systems," in *Toward a Theory on Biological and Physical Interactions in the World Ocean*, B. Rothschild (ed.), Kluwer Academic, Dordrecht, The Netherlands, 555-598 (1988).

2. T.D. Dickey, "Physical-optical-biological scales relevant to recruitment in large marine ecosystems," in *Large Marine Ecosystems: Patterns, Processes, and Yields*, K. Sherman, L.M. Alexander, and B.D. Gold (eds.), AAAS, Washington, DC, 82-98 (1990).

3. T. Dickey, "The emergence of concurrent high-resolution physical and bio-optical measurements in the upper ocean," *Rev. of Geophys.*, **29**, 383-413 (1991).

4. T. Dickey, T.C. Granata, and I. Taupier-Letage, "Automated *in situ* observations of upper ocean biogeochemistry, bio-optics, and physics and their potential use for global studies," in *Proc. of the Ocean Climate Data Workshop*, Goddard Space Flight Center, Greenbelt, MD, 317-353 (1993).

5. T. Dickey, A. Plueddemann, and R.A. Weller, "Current and water property measurements in the coastal ocean," *The Sea*, A. Robinson and K. Brink (eds.), in press (1996).

6. T. Dickey, R.H. Douglass, D. Manov, D. Bogucki, P.C. Walker, and P. Petrelis, "An experiment in duplex communication with a multivariable moored system in coastal waters," *J. Atmos. Ocean. Tech.*, **10**, 637-644 (1993).

7. K.L. Denman and T.M. Powell, "Effects of physical processes on planktonic ecosystems in the coastal ocean," *Ocean Mar. Biol. Ann. Rev.*, **22**, 125-168 (1984).

8. U.S. JGOFS Planning Report Number 18, "Bio-optics in U.S. JGOFS," T. Dickey and D. Siegel (eds.), 180pp. (1993).

9. U.S. GLOBEC Report Number 4, Workshop on Acoustical Technology and the Integration of Acoustical and Optical Sampling Methods," C. Greene, C. Greenlaw, V. Holliday, P. Ortner, R. Pieper, T. Stanton, and J. Traynor (eds.), 58pp. (1991).

10. U.S. GLOBEC Report Number 8, U.S. GLOBEC Workshop on Optics Technology," G. Paffenhofer and T.R. Osborn (eds.), 18pp. (1993).

11. SCOR, "Sampling and Observing Systems," *GLOBEC Report Number 3*, GLOBEC-International, T. Dickey (ed.), 99pp (1993).

12. SCOR, "An Advanced Modeling/Observational System (AMOS) for Physical-Biological-Chemical Ecosystem Research and Monitoring, a working paper/technical report prepared by GLOBEC.INT Working Groups on Numerical Modeling and Sampling and Observing Systems," *GLOBEC Report Number 3*, GLOBEC-International, A. Robinson and T. Dickey (eds.), (1996).

13. R.C. Smith, K.J. Waters, and K.S. Baker, "Optical variability and pigment biomass in the Sargasso Sea as determined using deep-sea optical mooring data," *J. Geophys. Res.*, **96**, 8665-8686 (1991).

14. J.L. Mueller and R.W. Austin, "Ocean optics protocols for SeaWiFS validation, *SeaWiFS Tech. Report Series,* NASA Tech. Mem. 104566, Goddard Space Flight Center, Greenbelt, MD, 43pp (1992).

15. B.H. Jones, A. Bratkovich, T. Dickey, G. Kleppel, A. Steele, R. Iturriaga, and I. Haydock, "Variability of physical, chemical, and biological parameters in the vicinity of an ocean outfall plume," in *Stratified Flows*: Proc. Third Int. Symp. on Stratified Flows, E.J. List and H.H. Jirka (eds.), ASCE, New York, 877-890 (1990).

16. L. Washburn, B.H. Jones, A. Bratkovich, T.D. Dickey, and M.-S. Chen, "Mixing, dispersion, and resuspension in vicinity of ocean wastewater plume," *J. Hydraul. Eng.*, **118**, 38-58 (1992).

17. W.S. Pegau, R.V. Zaneveld, and K.J. Voss, "Toward closure of the inherent optical properties of natural waters," *J. Geophys. Res.*, **100**, 13,193-13,221 (1995).

18. Coble, P.G., "Characterization of marine and terrestrial DOM in seawater using excitation-emission matrix spectroscopy, *Mar. Chem.*, **51**, 325-346 (1996).

19. A.A. Petrenko, B.H. Jones, T.D. Dickey, M. LeHaitre, and C. Moore, "Bio-optical characterization of the particle field in Mamala Bay, HI: effluent and naturally occurring particles, submitted *to J. Geophys. Res.*

20. S.L. Smith, R.E. Pieper, M.V. Moore, L.G. Rudstram, C.H. Greene, J.E. Zanon, C.M. Flagg, and C.E. Williamson, "Acoustic techniques for the *in situ* observations of zooplankton," *Archiv. fur Hydro-biologie Ergebnisse der Limnologie*, **36**, 23-43 (1992).

21. D.V. Holliday and R.E. Pieper, "Bioacoustical oceanography at high frequencies," in *Zooplankton Production*, Proc. of a Symp. held in Plymouth, England, R. Harris (ed.), *ICES J. of Mar. Sci.*, **52**, 279-296 (1995).

22. H.S.J. Roe and G. Griffiths, "Biological information from an acoustic Doppler current profiler," *Mar. Biol.*, **115**, 339-346 (1993).

23. H.S.J. Roe, G. Griffiths, M. Hartman, and N. Crisp, "Variability in biological distributions and hydrography from concurrent acoustic Doppler current profiler and SeaSoar surveys," *ICES J. of Mar. Sci.*, **53**, 131-138 (1996).

24. R.C. Smith and K.S. Baker, "Spatial and temporal patterns in pigment biomass in Gulf Stream warm-core ring 82B and its environs," *J. Geophys. Res.*, **90**, 8859-8870 (1985).

25. T. Dickey, J. Marra, T. Granata, C. Langdon, M. Hamilton, J. Wiggert, D. Siegel, and A. Bratkovich, "Concurrent high resolution bio-optical and physical time series observations in the Sargasso Sea during the spring of 1987," *J. Geophys. Res.*, **96**, 8643-8663 (1991).

26. T. Dickey, T. Granata, J. Marra, C. Langdon, J. Wiggert, Z. Chai-Jochner, M. Hamilton, J. Vazquez, M. Stramska, R. Bidigare, and D. Siegel, "Seasonal variability of bio-optical and physical properties in the Sargasso Sea," *J. Geophys. Res.*, **98**, 865-898 (1993).

27. J. Marra, T. Dickey, W.S. Chamberlin, C. Ho, T. Granata, D.A. Kiefer, C. Langdon, R. Smith, K. Baker, R. Bidigare, and M. Hamilton, "The estimation of seasonal primary production from moored optical sensors in the Sargasso Sea," *J. Geophys. Res.*, **97**, 7399-7412 (1992).

28. K.J. Waters, R.C. Smith, and J. Marra, "Phytoplankton production in the Sargasso Sea as determined using optical mooring data, *J. Geophys. Res.*, **99**, 18,385-18,402 (1994).

29. T.C. Granata, J. Wiggert, and T. Dickey, "Trapped, near-inertial waves and enhanced chlorophyll distributions," *J. Geophys. Res.*, **100**, 20,793-20,804 (1995).

30. J. Wiggert, T. Dickey, and T. Granata, "The effect of temporal undersampling on primary production estimates," *J. Geophys. Res.*, **99**, 3361-3371 (1994).

31. V.H. Strass, "Chlorophyll patchiness caused by mesoscale upwelling at fronts," *Deep-Sea Res.*, **39**, 23-43 (1992).

32. J. Aiken and I. Bellan, "Synoptic optical oceanography with the undulating oceanographic recorder, *Proc. SPIE-Int. Soc. Opt. Eng.*, **637**, 221-230 (1986).

33. A.F. Michaels and A.H. Knap, "Overview of the U.S. JGOFS Bermuda Atlantic Time-series Study," *Deep-Sea Res. II*, **43**, 157-198 (1996).

34. D.A. Siegel, A.F. Michaels, J.C. Sorensen, M. O'Brien, and M.A. Hammer, "Seasonal variability of light availability and utilization in the Sargasso Sea," *J. Geophys. Res.*, **100**, 8675-8713 (1995).

35. D.A. Siegel and A.F. Michaels, "Quantification of non-algal light attenuation in the Sargasso Sea: implications for biogeochemistry and remote sensing," *Deep-Sea Res. II*, **43**, 321-345 (1996).

36. T. Dickey, D. Frye, J. McNeil, D. Manov, N. Nelson, D. Sigurdson, H. Jannasch, D. Siegel, T. Michaels, and R. Johnson, "Upper ocean temperature response to Hurricane Felix as measured by the Bermuda Testbed Mooring, submitted to *Mon. Wea. Rev.* (1996).

37. J. Marra, "Marine bioluminescence and upper ocean physics: seasonal changes in the northeast Atlantic," *Oceanography*, **2**, 36-38 (1989)

38. T. Dickey, J. Marra, M. Stramska, C, Langdon, T. Granata, A. Plueddemann, R. Weller, and J. Yoder, "Bio-optical and physical variability in the subarctic North Atlantic Ocean during the spring of 1989," *J. Geophys. Res.*, **99**, 22,541-22,556 (1994).

39. M. Stramska and T.D. Dickey, "Phytoplankton bloom and the vertical thermal structure of the upper ocean," *J. Mar. Res.*, **51**, 819-842 (1993).

40. D.G. Ondercin, C.A. Atkinson, and D.A. Kiefer, "The distribution of bioluminescence and chlorophyll during the late summer in the North Atlantic: maps and a predictive model," *J. Geophys. Res.*, **100**, 6575-6590 (1995).

41. J.W. Murray, E. Johnson, and C. Garside, "A U.S. JGOFS Process Study in the equatorial Pacific (EqPac): introduction," *Deep-Sea Res. II*, **42**, 275-293 (1995).

42. W.S. Kessler and M.J. McPhaden, "The 1991-1993 El Nino in the central Pacific," *Deep-Sea Res. II*, **42**, 295-333 (1995).

43. J.A. Yoder, S.G. Ackleson, R.T. Barber, P. Flament, and W.M. Balch, "A line in the sea," *Nature*, **371**, 689-392 (1994).

44. D.L. Rudnick, R.A. Weller, C.C. Eriksen, T.D. Dickey, J. Marra, and C. Langdon, "One-year moored observations of the Arabian Sea monsoons," submitted to *EOS* (1996).

45. D.E. Sigurdson, T.D. Dickey, and D. Manov, "Arabian Sea Mooring Data Report," *Univ. of Calif., Santa Barbara Ocean Physics Laboratory Tech. Rep.* **OPL-2-95**, 26pp (1995).

46. D.E. Sigurdson, T.D. Dickey, and D. Manov, "Arabian Sea Mooring Data Report," *Univ. of Calif., Santa Barbara Ocean Physics Laboratory Tech. Rep.* **OPL-2-96**, 26pp (1996).

47. A.J. Weeks, G. Griffiths, H. Roe, G. Moore, I.S. Robinson, A. Atkinson, and R. Schreeve, "The distribution of acoustic backscatter from zooplankton compared with physical structure, phytoplankton, and radiance during the spring bloom in the Bellingshausen Sea," *Deep-Sea Res.*, **42**, 997-1019 (1995).

48. K.H. Brink and T.J. Cowles, "The Coastal Transition Zone Program," *J. Geophys. Res.*, **96**, 14,637-14,648.

49. M.R. Abbott, K.H. Brink, C.R. Booth, D. Blasco, L.A. Codispoti, P.P. Niiler, and S.R. Ramp, "Observations of phytoplankton and nutrients from a Lagrangian drifter off northern California," *J. Geophys. Res.*, **95**, 9393-9409 (1990).

50. B.H. Jones, C.N.K. Mooers, M. Reinecker, T. Stanton, and L. Washburn, "Chemical and biological structure of a cool filament observed off northern California in July 1986 (OPTOMA21), *J. Geophys. Res.*, **96**, 22,207-22,2225 (1991).

51. L. Washburn, D.C. Kadko, B.H. Jones, T. Hayward, P.M. Kosro, T.P. Stanton, S. Ramp, and T. Cowles, "Water mass subduction and the transport of phytoplankton in a coastal upwelling system," *J. Geophys. Res.*, **96**, 14,927-14,946 (1991).

52. D. Bogucki, T. Dickey, and L.G. Redekopp, "Sediment resuspension and mixing by resonantly-generated internal solitary waves," *J. Phys. Oceanogr.*, in press (1996).

53. P.E. Biscaye, C.N. Flagg, and P.G. Falkowski, "The Shelf Edge Exchange Processes experiment, SEEP-II: an introduction to hypotheses, results, and conclusions," *Deep-Sea Res. II*, **41**, 231-252 (1994).

54. C.D. Wirick, "Exchange of phytoplankton across the continental shelf-slope boundary of the Middle Atlantic Bight during spring 1988," *Deep-Sea Res. II*, **41**, 391-410 (1994).

55. C.N. Flagg, C.D. Wirick, and S.L. Smith, "The interaction of phytoplankton, zooplankton, and currents from 15 months of continuous data in the Mid-Atlantic Bight," *Deep-Sea Res. II*, **41**, 411-435 (1994).